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Accurate wind turbine aero-acoustics by high-order schemes

Zhu, Wei Jun; Shen, Wen Zhong; Sørensen, Jens Nørkær

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Wei Jun Zhu, Wen Zhong Shen, Jens Nørkær Sørensen
DTU-Wind, Lyngby
wjzh@dtu.dk

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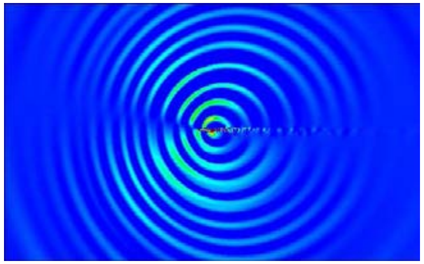


Introduction

- Objective
  - to develop a CAA tool for predicting *flow induced noise*

- Method
  - High-order Flow/Acoustics splitting technique
  - computational fluid dynamics + computational aero-acoustics

- Challenges
  - small amplitude of sound waves, e.g., 75dB $\rightarrow$ $p' = 10^{-6}\ p_0$
  - wide range of frequencies , 20Hz-20kHz
  - long computing time

CFD - EllipSys Flow Solver

- Incompressible flow solver - EllipSys
  - Finite volume method
  - Cell-centred / Multi-block
  - Five levels multi-grid for the pressure equation
  - SIMPLE / SIMPLEC with Rhie-Chow interpolation
  - Second-order both in space and in time

- RANS / *k-ω, k-ε, SA, etc.*

- LES - The filtered incompressible Navier-Stokes equations

momentum equations: $$\frac{\partial \overline{U}_i}{\partial t} + \frac{\partial \left(\overline{U}_i \overline{U}_j\right)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \nu \frac{\partial^2 \overline{U}_i}{\partial x_j^2} + \frac{\partial \tau_{ij}}{\partial x_j}$$

turbulent stress terms: $$\tau_{ij} = \nu_t \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) - \frac{2}{3} k \delta_{ij}$$

the eddy viscosity: $$\nu_t = C \left| \vec{\overline{\omega}} \right|^{\alpha} k^{(1-\alpha)/2} \Delta^{(1+\alpha)}$$

CAA - EllipSys Aeroacostics Solver

- High-order CAA solver
  - Wavenumber optimized finite difference schemes
  - 4^{th}, 6^{th}, 8^{th}, 10^{th}, 12^{th} - order explicit and compact schemes in space
  - 4^{th} - order R-K for time advancing
- CAA equations:

$$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} = S$$

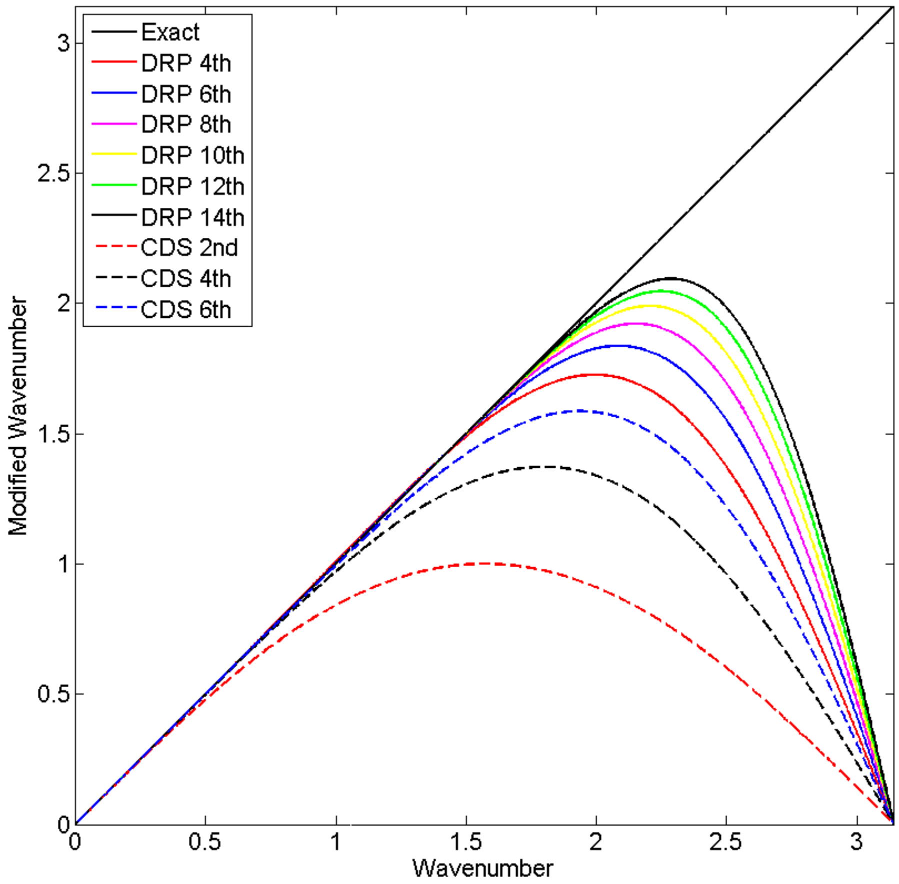
$$Q = \begin{pmatrix} \rho' \\ \rho u' + \rho' U \\ \rho v' + \rho' V \\ \rho w' + \rho' W \\ p' \end{pmatrix}, E = \begin{pmatrix} \rho u' + \rho' U \\ \rho(2Uu' + u'^2) + \rho' U^2 + p' \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(Wu' + Uw' + u'w') + \rho' UW \\ c^2(\rho u' + \rho' U) \end{pmatrix}$$

$$F = \begin{pmatrix} \rho v' + \rho' V \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(2Vv' + v'^2) + \rho' V^2 + p' \\ \rho(Vw' + Wv' + v'w') + \rho' VW \\ c^2(\rho v' + \rho' V) \end{pmatrix}$$

$$G = \begin{pmatrix} \rho w' + \rho' W \\ \rho(Wu' + Uw' + u'w') + \rho' UW \\ \rho(Wv' + Vw' + v'w') + \rho' VW \\ \rho(2Ww' + w'^2) + \rho' W^2 + p' \\ c^2(\rho w' + \rho' W) \end{pmatrix}, S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ -\frac{\partial P}{\partial t} \end{pmatrix} \qquad c^2 = \frac{\gamma p}{\rho} = \frac{\gamma(P + p')}{\rho_0 + \rho'}$$

CAA – High order scheme

- Example of high-order schemes – DRP schemes and CDS schemes

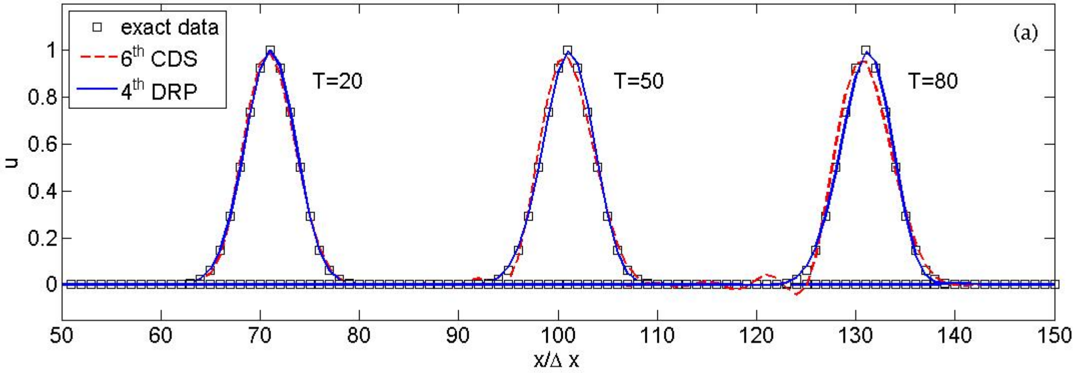


Simulation 1.– *Wave convection*

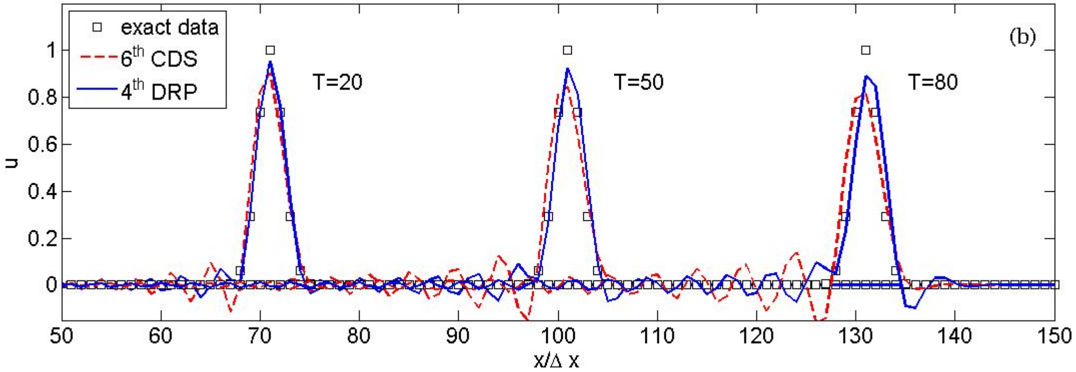
Wave convection: *∂u/∂t+∂u/∂x=0*

$$u = \exp(-\ln(2)(x - x_0)^2 / b^2)$$

b=3



b=1.5



Simulation 2.– *Wave scattering*

Initial disturbance: $p(x,y,0)=\exp\left[-\ln(2)\dfrac{(x-4)^2+y^2}{(0.2)^2}\right]$

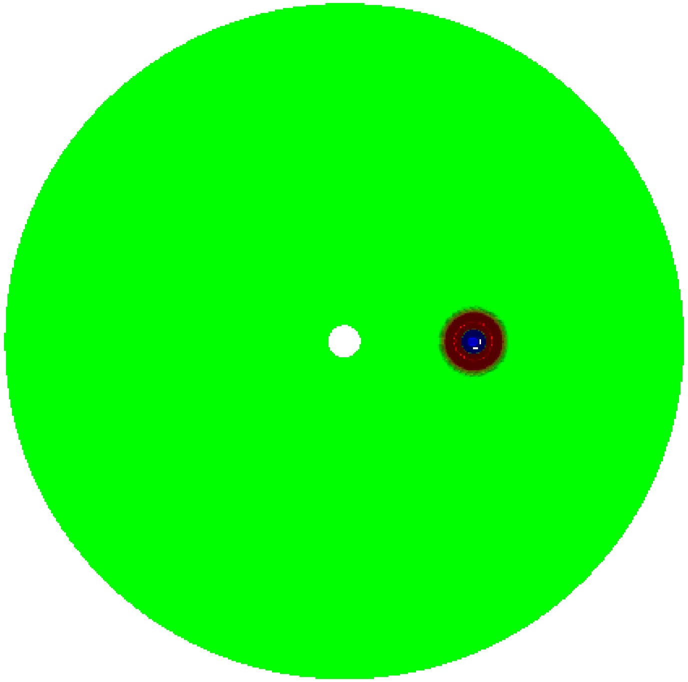
Initial velocity: $v_r=v_\theta=0$

Euler equation in polar frame:

$$\frac{\partial}{\partial t}\begin{pmatrix} v_r \\ v_\theta \\ p \end{pmatrix}+\frac{\partial}{\partial r}\begin{pmatrix} p \\ 0 \\ v_r \end{pmatrix}+\frac{1}{r}\frac{\partial}{\partial \theta}\begin{pmatrix} 0 \\ p \\ v_\theta \end{pmatrix}+\frac{1}{r}\begin{pmatrix} 0 \\ 0 \\ v_r \end{pmatrix}=0$$

Mesh configuration: 201x201 points in a half domain

Schemes: 4th-DRP and 4th-RK



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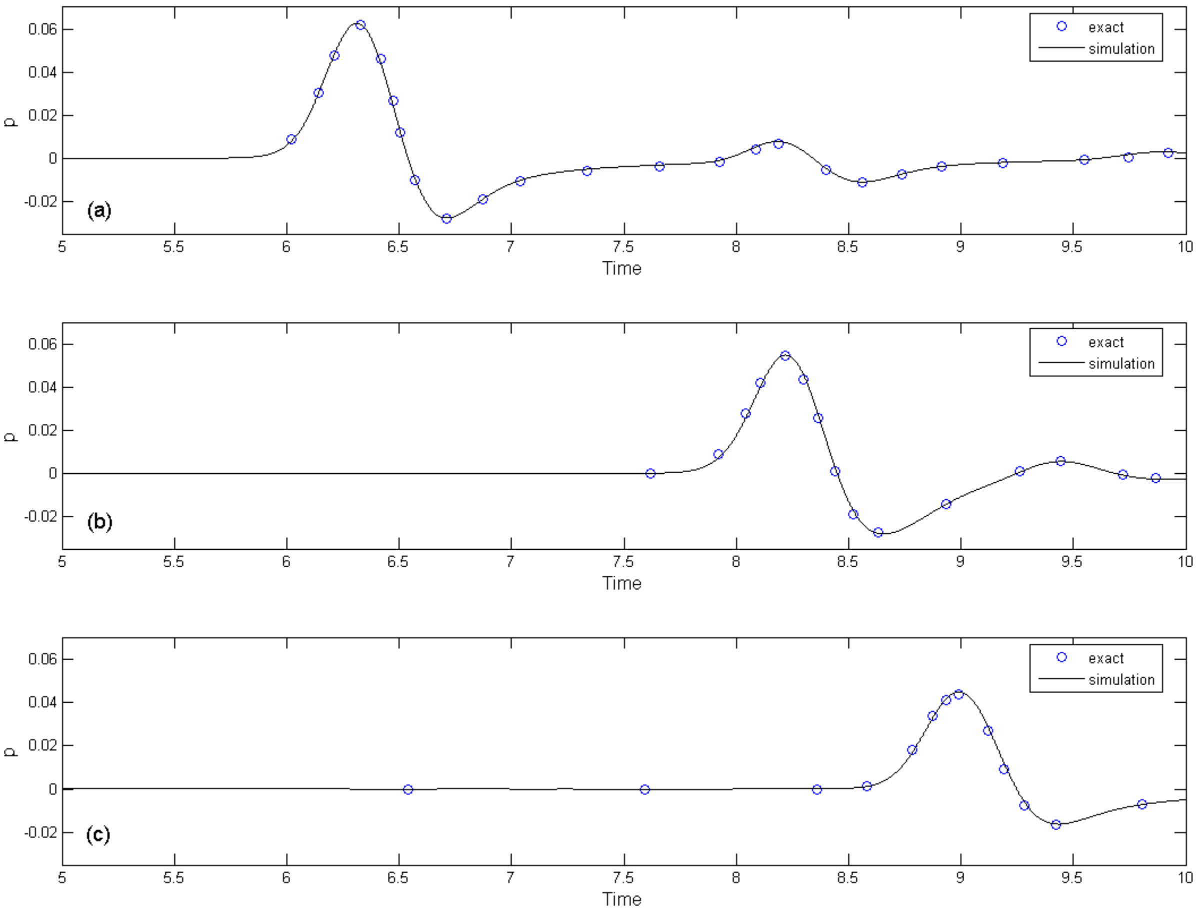
Simulation 2.– *Wave scattering*



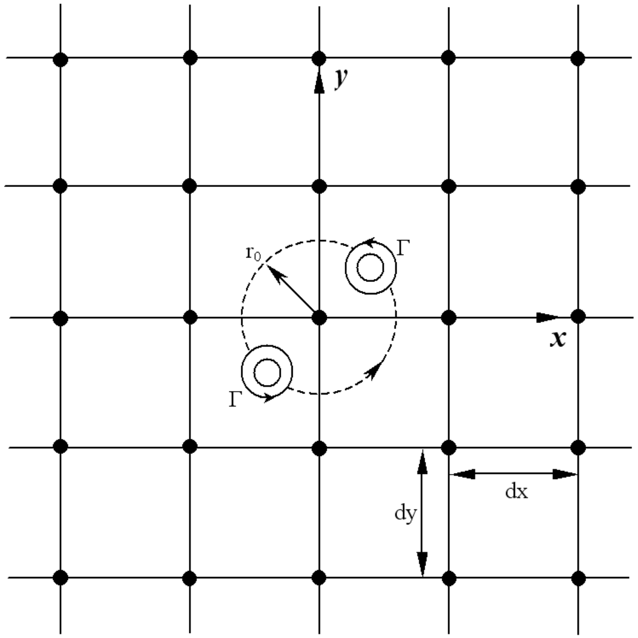
Time history sound pressure p(t) measured at :
r = 5, A (θ = 90 deg), B(θ = 135 deg), C (θ = 180 deg).

Simulation 3.– *Vortex sound*

The flow field variables U,V,P are given as:

$$U - iV = \frac{\Gamma}{i\pi}\frac{z}{z^2 - b^2}$$

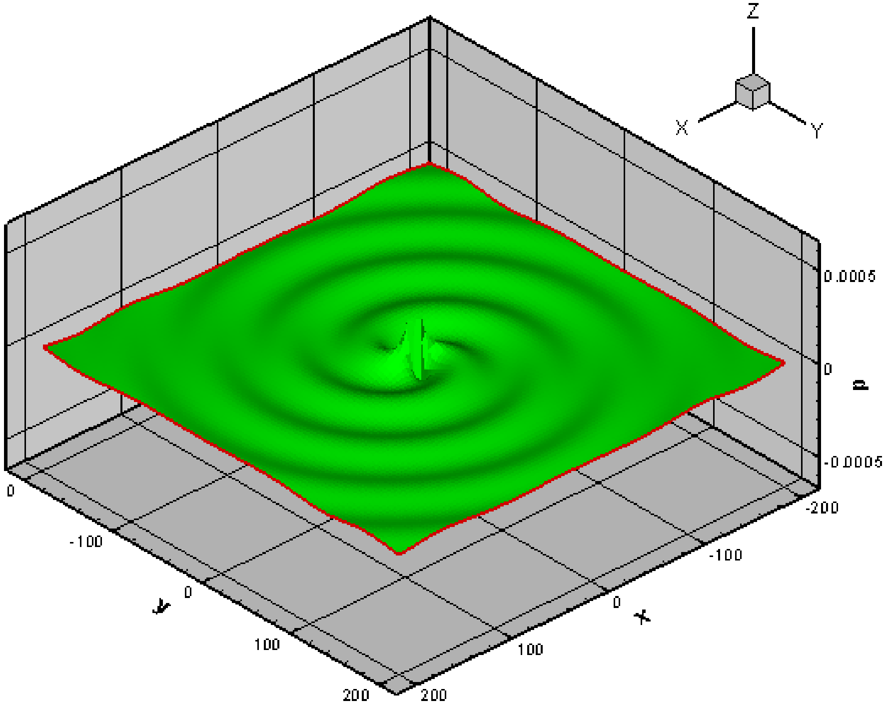
$$P = P_0 + \rho_0 \frac{\Gamma\omega}{\pi}\Re\left(\frac{b^2}{z^2 - b^2}\right) - \frac{1}{2}\rho_0 (U^2 + V^2)$$

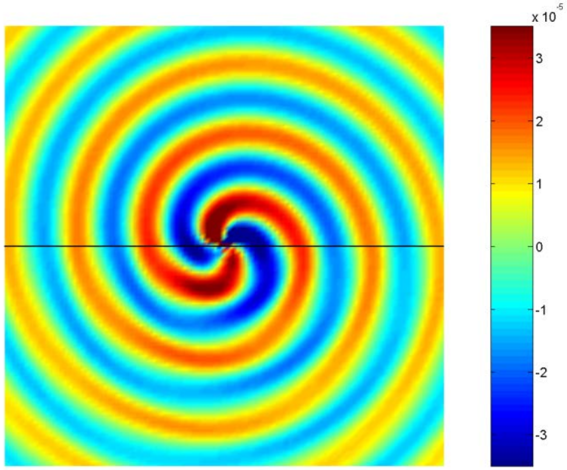


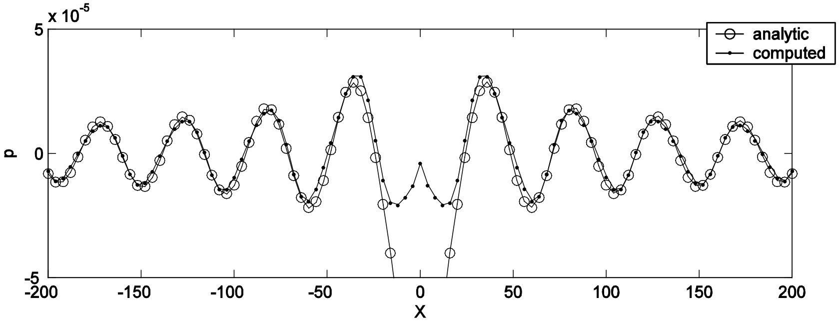
u’,v’,ρ’,p’ are found from the 2D acoustic equations:

$$\frac{\partial}{\partial t}\begin{pmatrix} \rho' \\ \rho u' + \rho' U \\ \rho v' + \rho' V \\ p' \end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix} \rho u' + \rho' U \\ \rho(2Uu' + u'^2) + \rho' U^2 + p' \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ c^2(\rho u' + \rho' U) \end{pmatrix} + \frac{\partial}{\partial y}\begin{pmatrix} \rho v' + \rho' V \\ \rho(Vu' + Uv' + u'v') + \rho' UV \\ \rho(2Vv' + v'^2) + \rho' V^2 + p' \\ c^2(\rho v' + \rho' V) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -\dfrac{\partial P}{\partial t} \end{pmatrix}$$

Simulation 3.– *Vortex sound*





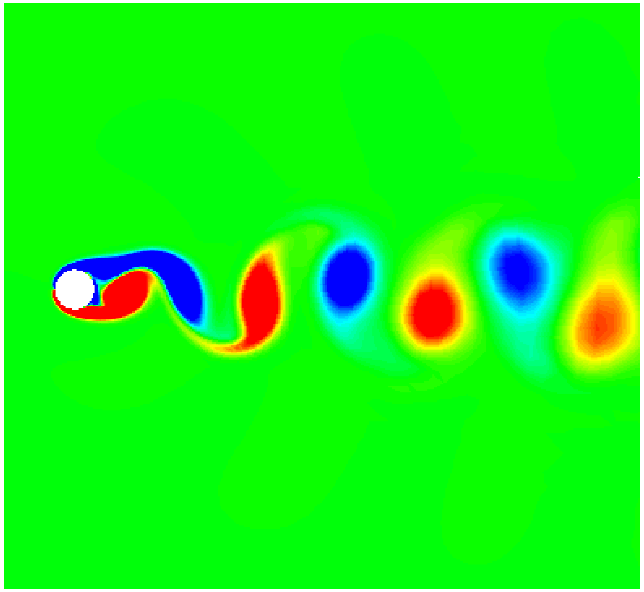


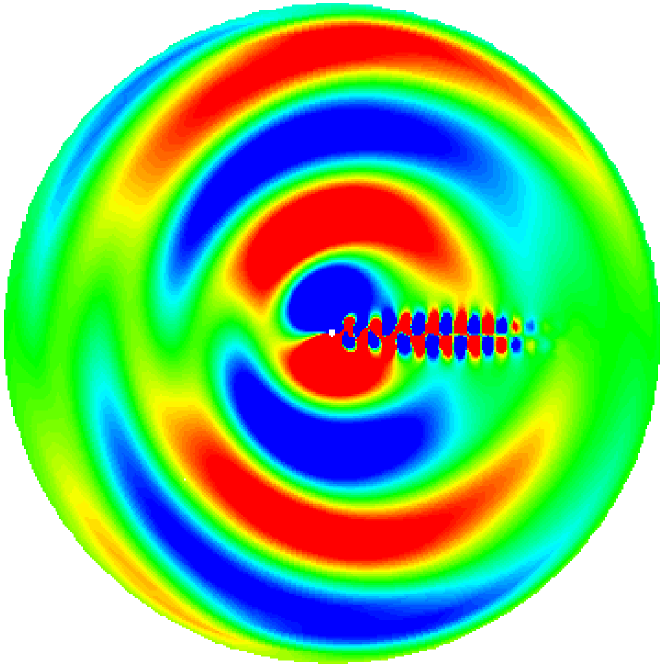
$\Gamma = 2\pi / 10$

Simulation 4.– *Laminar flow over cylinder*

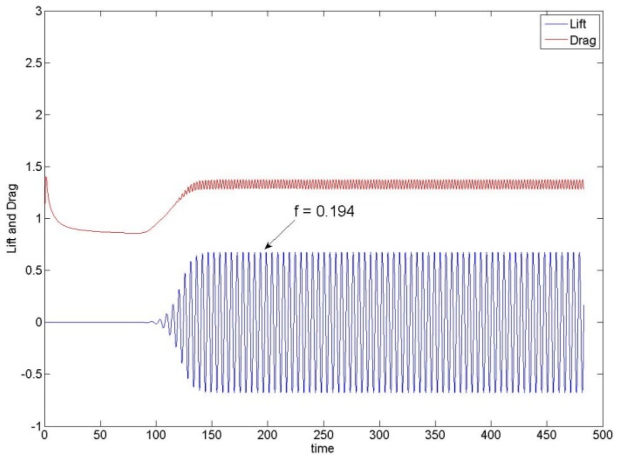
Flow over a cylinder at Re = 200 and M = 0.2.

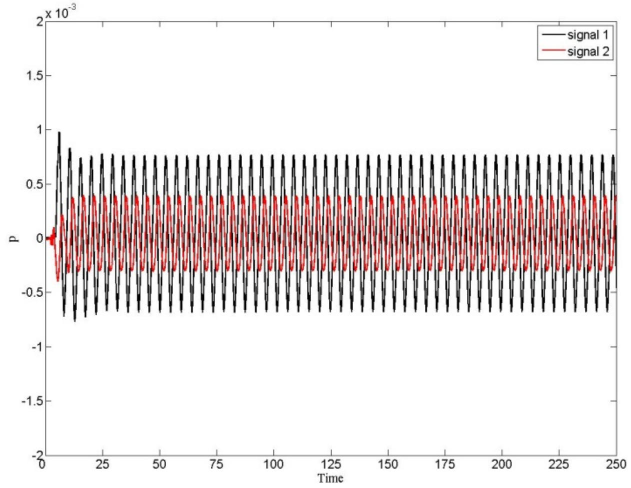
O-mesh: 256x128 points in the tangential and radial directions; dt = 1e-3

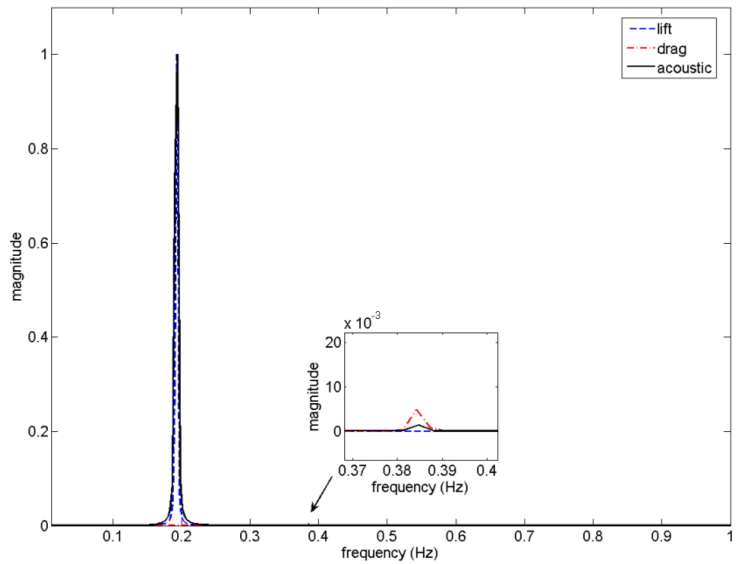




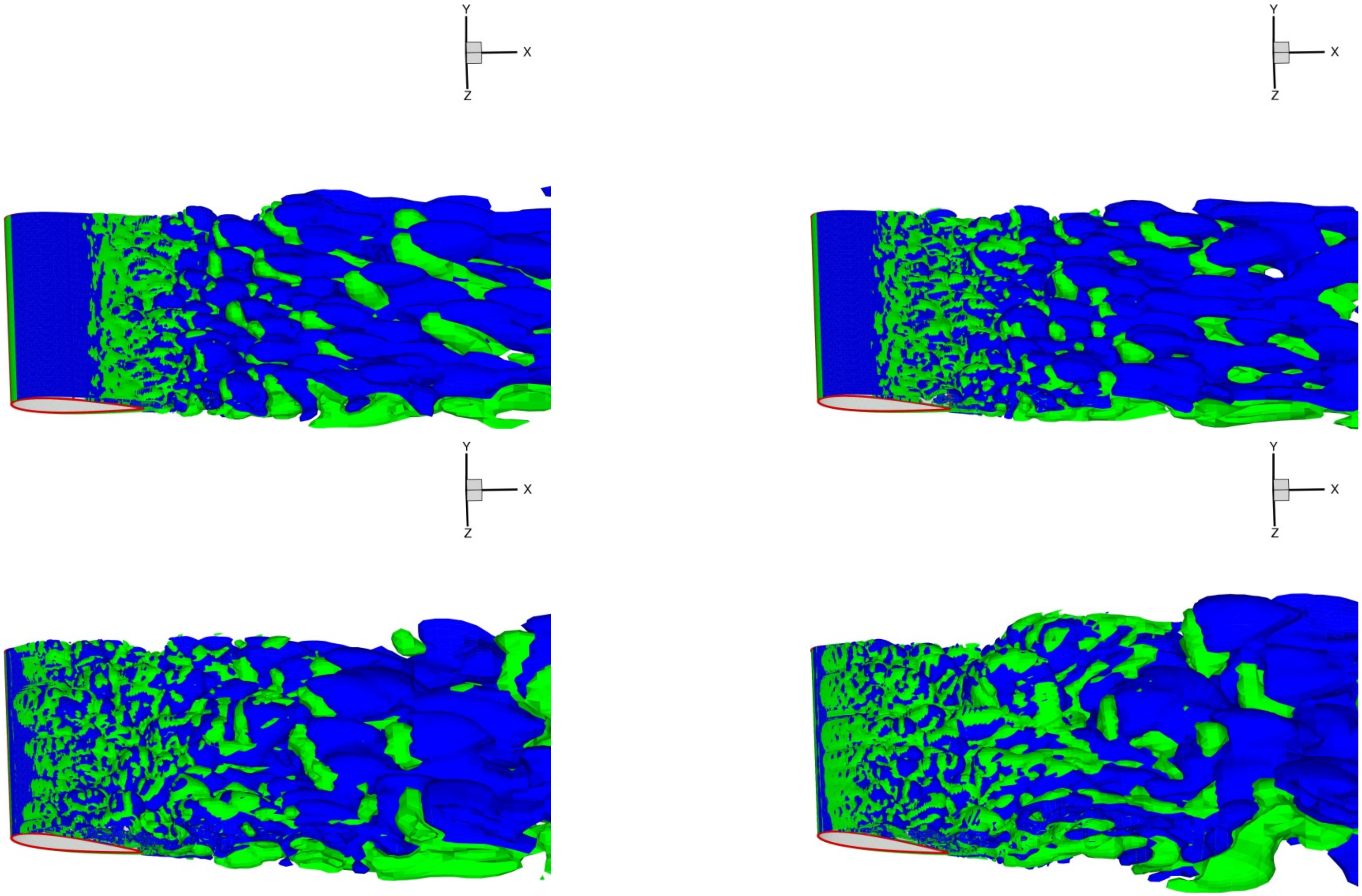
Simulation 4.– *Laminar flow over a cylinder*





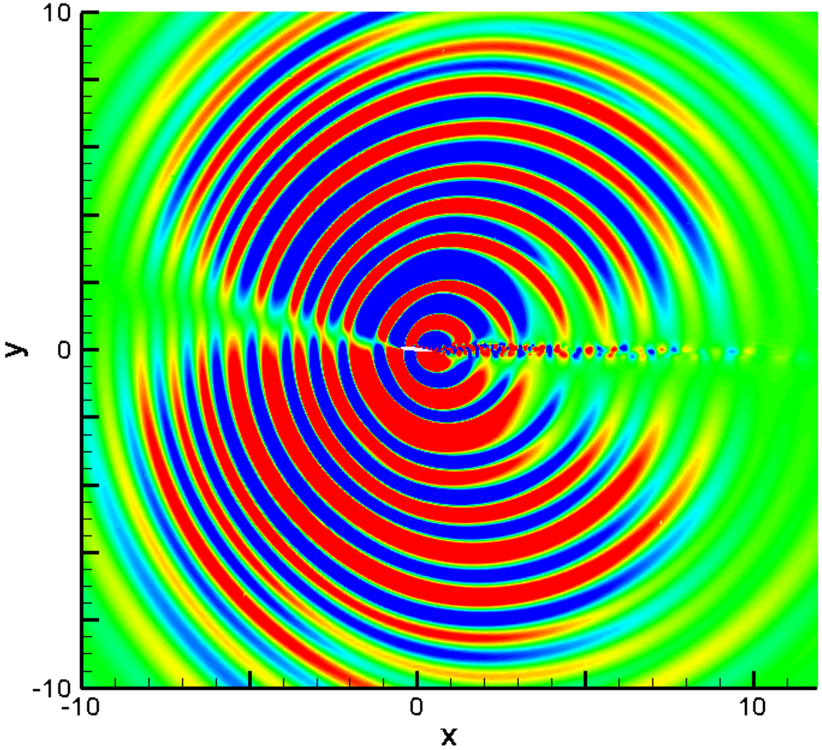


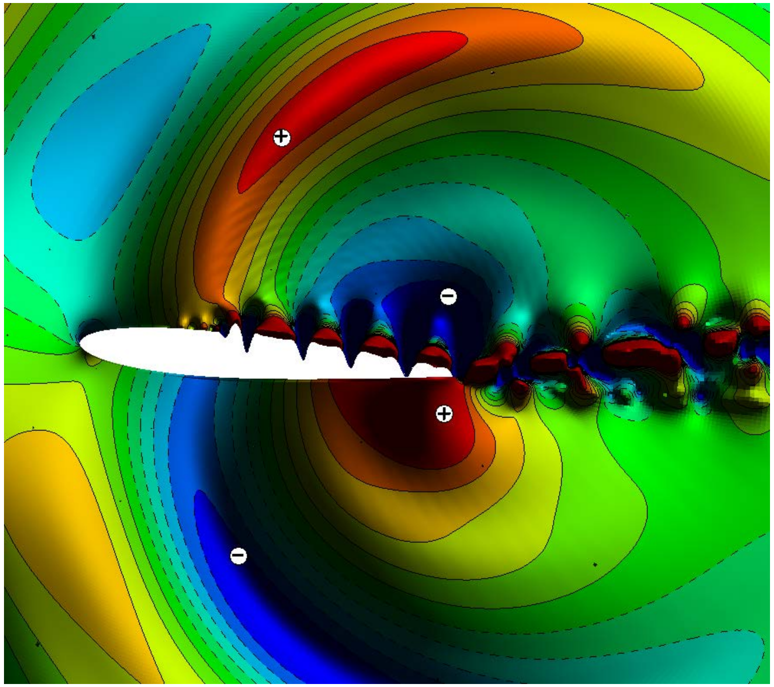
Simulation 5.– *Turbulent flow over an airfoil*



Re = 160,000 and α= 4° ,6° ,10° ,12° .

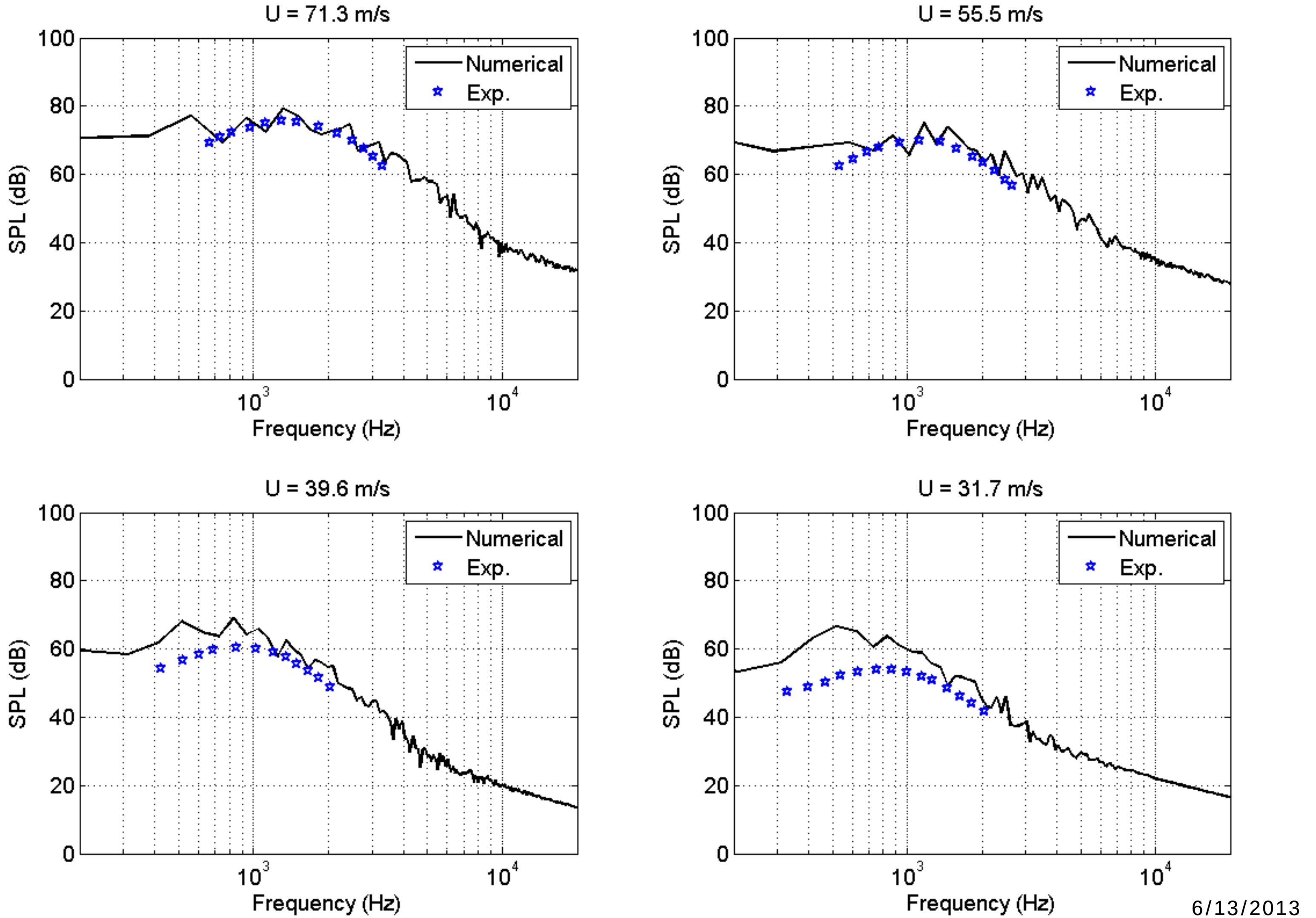
Simulation 5.– *Turbulent flow over an airfoil*





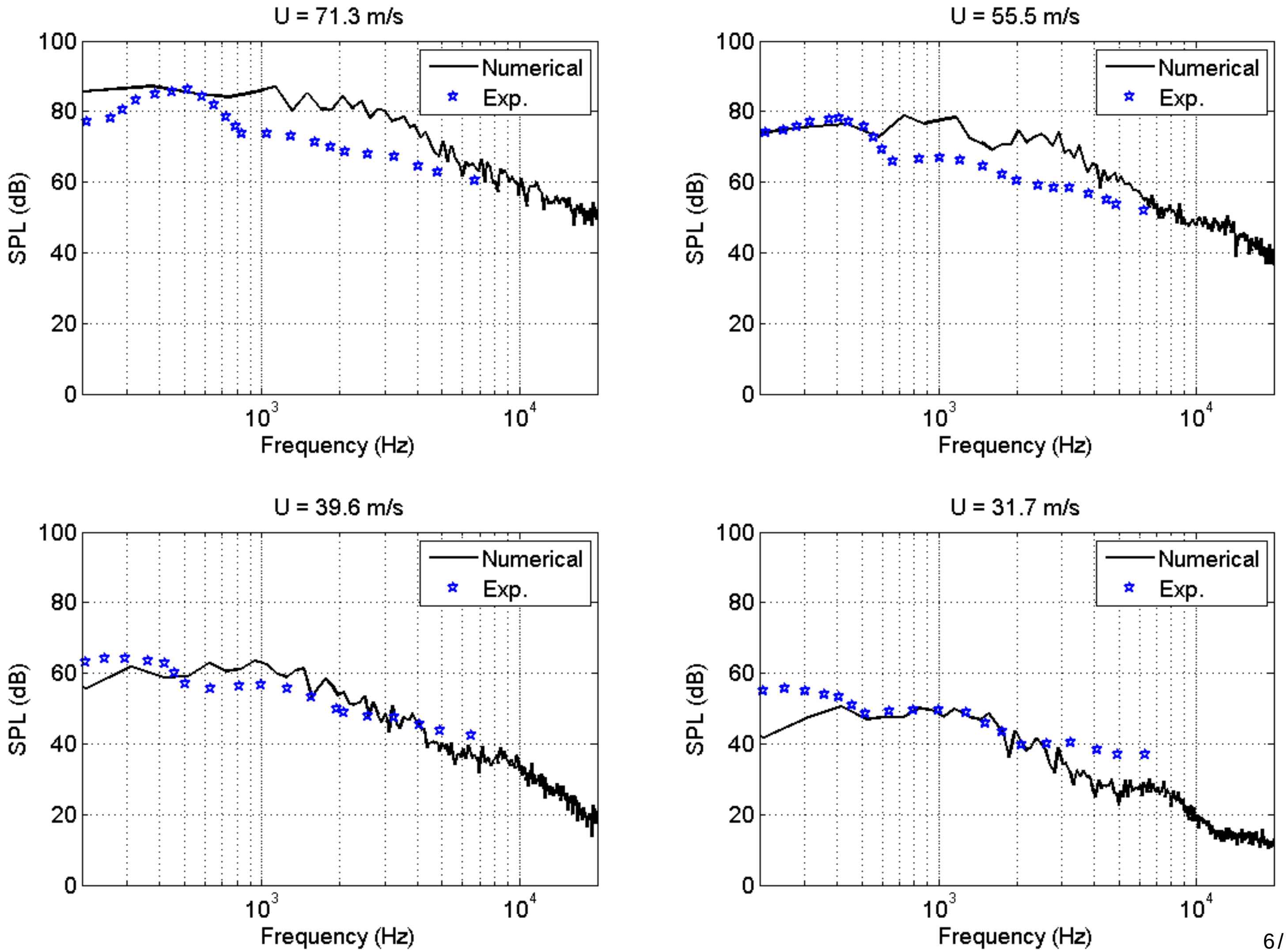
Simulation 5.– *Turbulent flow over an airfoil*

- Turbulent airfoil flow: α = 6.7° .



Simulation 5.– *Turbulent flow over an airfoil*

- Turbulent airfoil flows - α = 12.3° .



Conclusions

- Instead of directly solving the compressible NS equations, flow induced noise is predicted by the flow/acoustic splitting method.
- Flow and acoustic simulations were carried out by EllipSys using HPC (cluster with over 500 nodes).
- To reduce dispersion errors of sound waves, high-order schemes are used for CAA equations.
- It is observed that the aerodynamic force is related to the noise generation (some correlations are found from their spectra).
- For turbulent flows, LES is a good option for flow computations. However, for high-Reynolds-number-flow, LES becomes expansive.

Thank you very much for your attention!